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FABRICATION OF FUNCTIONALLY GRADED COMPOSITE MATERIAL USING POWDER METALLURGY ROUTE: AN OVERVIEW

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ABSTRACT

Functionally Graded Composite Material (FGCMs) are inhomogeneous materials, consisting of two (or more) different materials, with an engineered gradient along the thickness direction having a continuously varying spatial composition. Keeping in mind the wide areas of application and the probable scope of such materials, some existing problems are discussed. As part of the present investigation, a simple experimentation involving Al-SiC and Al-Al_2O_3 FGCM, by powder metallurgy (PM) route has been carried out and discussed. The effect of SiC and Al_2O_3 addition on the density of Aluminium, in the proposed functionally graded composite material and an overview of the current status of research on FGCMs including its future development is presented here. This review is about establishing powder metallurgy (PM) as a better technique for large scale production and up scaling of FGCM. This was further strengthened after considering the benefits of the technique such as process cost efficiency, authenticity of the functional application of the process and high adequacy of the process to control the quality of the FGM.

KEYWORDS: Functionally Graded Composite Material (FGCM), Fabrication, Powder Metallurgy (PM) & Sintering

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Original Article

INTRODUCTION

Joining of two or more dissimilar materials in the laminar form, often lead to failure owing to delamination, because of poor bonding between the materials as well as load bearing characteristic of the materials. Functionally Graded Material (FGM), has compositional and micro structural gradient, along its thickness direction was developed as an answer to the above mentioned failures. These works comprises of combining the metal–ceramics in a definite gradient and find their respective characteristics, and compare the same with the results of other authors and recognize practical application of the new material, developed in our daily use. While, trying to establish the appropriate method to implement the process, the paper presents an extensive review on the different solid state fabrication (SFF) methods of FGM composed of metal and ceramic phases. Fabrication methods in this field of work used varied ideas from different backgrounds of gradation and consolidation or Sintering methods. However each of these methods has its own pros and cons and the best method to be applied can be identified by considering some critical issues which has been pointed out in published literatures. FGCMs exhibit flexibility in terms of functional behavior of a single material as on one side it may exhibit metal like properties on the other side it will exhibit high temperature withstanding characteristics. This tailoring of material properties in FGCMs is done by controlling factors like chemical composition, microstructure or atomic orders etc, the property can vary along a gradient along its thickness direction [1,2]. Most theoretical works on designing, investigating and detailing the preparation of FGMs indicates the process mainly comprises of two steps viz.

gradation and consolidation. Gradation process is performed either by consecutive homogenization or by segregation process. Consecutive process is about building the FGM with a stepwise gradient using powder metallurgy; homogenizing process shows a sharp interface between two materials which is converted into a single gradient by a material transport and in segregating process, indicates the changing of a visibly uniform material into a single gradient also by material transport which is caused by an external field like electric or gravitational.

In order to successfully fabricate the FGM specimens, scholars and researchers have applied the best methods or combination of several methods depending on the characteristics of the constituent materials [3, 4] by arranging one layer atop another with more than one starting material selectively until layered structure is produced. The benefits of this method are that it is able to produce unlimited number of gradients. In a PM process, the primary step in fabricating FGCMs is preparing the gradient (also known as gradation process) and can be based on porosity, volume fraction of the phases, particle sizes and even the chemical composition of elemental powders. Thus, it is concluded that the gradation process does not depend on the consolidation process. Thus it is immaterial, to know how the graded structure was achieved; the consolidation is a complete new subject of study. In sintering process, the bonding between the graded layers is the main concern and largely relies on the sintering process of the structure. The existing and the latest techniques of FGM fabrication will be discussed in the following part of the work and optimizing the same for a particular application has been the challenge.

The concept of functionally graded material (FGM) was introduced to meet the challenges of very high temperature environment and to eliminate the stress singularities [5-6]. Normally traditional composites made out of two different materials have often been used to great satisfaction for high performance demands. However stress singularities in such composites may occur at the interfacing layers owing to mismatch of materials. Considering high temperature environment, for example in the engine combustion chamber of an air vehicle or a nuclear fusion reactor, the relative higher mismatch in thermal expansion coefficient will induce greater residual stresses resulting in cracking or debonding of the composite. Therefore the concept of FGMs was introduced to meet these challenges of multifunctional materials in these adverse operating conditions [7, 37-38]. An FGM can be fabricated by continuously changing the constituents of multiphase materials in a predetermined volume fraction of the constituent material [8-10]. Owing to the continuous change in material properties of an FGM, the sharp interface between two materials disappear but the characteristics of two or more different material of the composite are preserved. Later on the stress singularity at the interface of a composite can be eliminated and thus bonding strength enhanced. Studies show that, the thermal residual stresses can be drastically reduced by using FGM [11-13]. Power-law function [14-15] and exponential function [16-21] are popularly used, to describe the variations of material properties of FGM, because of the wide material variations and applications of FGMs, literatures corresponding to FGMs, in the material constituent [22-24], and processing [9, 25] have significantly increased in the past decade. Many scholars and researchers are pursuing their research in the above field, to understand the mechanics and mechanism of FGMs, to offer an optimum profile for designers. Hence, it has been an earnest effort at establishing one such optimal profile, for a FGM using Aluminium with Silicon carbide and /Alumina here.

FGM concept may be applied for a thermal barrier, using a plate or shell like structure. There are many engineering applications including aircrafts, space vehicles, reactor vessels etc where metal-ceramic composite plates are widely used. Application of a high external pressure on the composite plate structure induces higher stresses, leading to adverse effect on its structural integrity and makes it susceptible to failure. Thus, it is pertinent to understand the mechanical behavior of an FGM plate, to assess the safety of the plate structure. Woo and Meguid [26], tried to obtain the analytical solution, for the plates and

shell under transverse mechanical loads and a temperature field, subjected to large deformations using the Karman theory. Reddy et al [27] investigated the static and dynamic responses of functionally graded ceramic–metal plates, by using a plate unite element that accounts for the transverse shear strains, rotary inertia and moderately large rotations in the Von Karman sense. He et al. [28] studied about the vibration control of the FGM plates with integrated piezoelectric sensors and actuators using finite element formulation, based on the classical laminated plate theory. Elastic bifurcation buckling of FGM plates under in-plane compressive loading was studied based on a combination of micromechanical and structural approaches [29].

FUNCTIONALLY GRADED COMPOSITE MATERIAL-A CONCEPT

As shown in the figure below, Functionally Graded Composite Materials (FGCMs) are prepared in two types of graded structures. Figure 1 (a) A step wise graded structure, while Figure1 (b) A continuous graded structure. While in case of step wise graded structure the micro structure, exhibit changes in stepwise manner which is similar to a multi-layered structure with interface existing between the discreet layers. But in case of figure (b) the change in composition, microstructure occurs continuously with position. The figure below depicts the concept in a very clear manner for a FGCM [3].

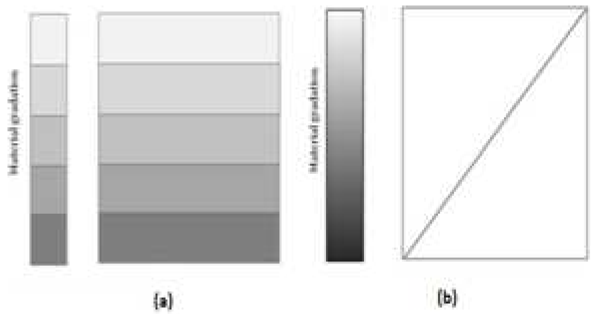

Figure.1: Schematic Diagram of FGCM Gradation Concept

FABRICATION TECHNIQUES FOR FGM

There are many physical and chemical methods depending on type of materials, potential application and available facilities for the FGMs fabrication [30]. Primarily the techniques are grouped in to constructive and transport based processes, where each of them is composed of several sub-steps that need to be followed to complete the fabrication. The implementation of constructive process which mandates full and potentially automated control of compositional gradients, the gradation process is made by stacking more than one starting materials selectively until layered structure is produced. The benefit of this method is; it is able to produce unlimited number of gradients. The transport based method is the prudent method for such cases as the case utilizes natural transport phenomena to create compositional and micro structural gradients during fabrication of the FGMs. The existing and most updated techniques for FGMs fabrication will be discussed in the following part of the work.

POWDER METALLURGY (PM)

It covers a wide range of ways in which materials and components are made from metal and ceramic powders. PM is also used to make intricate shape objects which are impossible to be made from other techniques. One of the most important products of this type is tungsten carbide based cutting tools. There are four basic steps in PM i.e. powder weighing, powder mixing, die compaction and sintering. Compaction is generally done at room temperature, and sintering at the elevated-temperature usually under controlled atmosphere. Secondary processing such as coining or repressing and re-sintering

often follows sintering to obtain special properties or to have enhanced precision. PM is an appropriate technology for the FGMs fabrication and is widely being used to create gradients on material. This method is best suited for FGCMs fabrication using solid materials. In PM route, some steps are needed for the completion of the product preparation. These steps can be classified into four categories, namely: powder preparation, powder processing (weighing and mixing of powder according to desired percentage of composition), forming operations (stacking and ramming of premixed powders) and finally sintering or pressure assist hot consolidation. After completing the sintering process, optional secondary processing can be performed to enhance the performance and characteristics of the structure. Figure 2 describes flow process chart for powder metallurgy process.

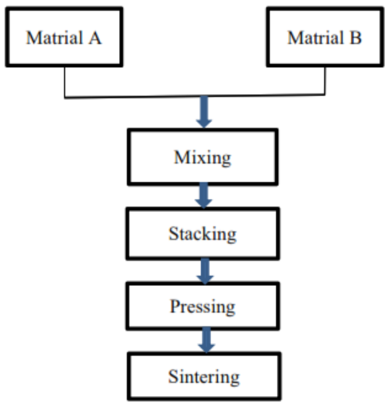

Figure.2. Flow Process Chart for Powder Metallurgy Process

Many techniques have been developed for powder preparation like through chemical reactions, electrolytic deposition, grinding or comminution. Such techniques allow mass production rates of powder form materials and it is usually offered within controllable size range of the final grain population. For the powder processing, the main consideration is focused on the precision in weighing amounts and the dispersion of the mixed powders. These parameters will dictate the structure properties and hence must be handled carefully. In the subsequent processes, the forming operations is performed at room temperature while sintering is conducted at atmospheric pressure as the elevated temperature used may cause other reaction that may affect the materials. At this stage, the atmosphere in the sintering furnace ought to be appropriate since high-temperature process has high sensitivity to the surroundings. Within a customized sintering profile for the fabrication, a new composition profile of 15 layers with crack free joint of the FGM was proposed by Lee et al [31] as the optimized structure. Instead of the ceramics FGM, a bulk SiC/C FGM is another pair that is successfully fabricated, using hot pressing process. In term of thermal properties, the hot- pressed SiC/C FGM was found having high effective thermal conductivity, at the interface of 1 mm SiC layer, when compared to the specimens prepared using other methods. No cracks were found on the SiC/C coatings, thus make the FGM possess high thermal fatigue behavior.

FGCM CHARACTERISTICS

Exclusive Properties of FGM’s

FGCM, as a material component with certain engineered property, changing continuously in space in a particular direction, as shown in figure above, as a result it can overcome the deficiencies exhibited by the traditional materials. Erdogan et al [32], opined through their work of the many advantages, over conventional and composite materials. FGM has the

following advantages:

- Residual stress and Thermal stress can be reduced using FGM coatings and interface layers.
- End point stress singularity and stress at the interface can be removed through FGM coatings.
- Reduction in crack propagating force and increasing the strength of the interface through FGM coatings.
- As an interface layer to connect two incompatible materials, FGMs can effectively enhance the bond strength.

Applications Oriented Classifications of FGMs

As the demand for newer materials to meet the growth and challenges of technological advancement grew with time, the concept of Functionally Graded Materials emerged with a variety of application areas as shown in Table 1, [33][34]. Considering the material combinations, FGMs are classified in to Metal / Ceramic, Ceramic/Ceramic, Ceramic/Plastic and many other combinations of materials.

CONSTRAINTS IN FABRICATION OF FGCM

Just as developing new engineered materials is an intriguing aspect from the user's view point, at the same point there are issues that need to be addressed and require further study mainly on the following areas [35]:

- Adequate database of the gradient material (including material system, parameters, material preparation, performance evaluation is to be developed.
- A focused research on variation of gradient material be aligned with respect to thermal stress relaxation of the materials as well as keep the road open to different applications in engineering field

Table 1: List of Different Types of FGCM (V. Richter et al 1995)

Sl. No.	FGCM Type	Requirement	Application
1	Al / SiC	Hardness & Toughness	Combustion Chambers
2	Al / C	_	Drive shaft, Turbine Rotors, Turbine Wheels
3	Si C / SiC	Corrosion Resistance and hardness	Combustion Chambers
4	Al / SiC	_	Fly wheels, Racing Car Brakes
5	Al_2O_3 / Al-alloy	Good Thermal & corrosion resistance	Rocket Nozzle, wings, Rotary Launchers, Engine casing

- A focused research on variation of gradient material is aligned with respect to thermal stress relaxation of the materials as well as keeps the road open to different applications in engineering field.
- FGMs prepared are samples of small size, simple structure. More practical valued materials are yet to be developed.
- Cost of manufacturing is high.
- Further research and evaluation of the physical properties of the material model are desired. Microscopic structure

and the quantitative relation between preparation conditions have to be established in order to accurately and reliably predict the physical properties of graded materials. Improved continuum theory, quantum (discreet) theory, percolation theory, microstructure model and advanced simulation method with high end computing facility, for simulating the material properties for theoretical prediction of the functionally graded composite characteristics.

APPLICATIONS OF FGCMS

- FGM was originally developed for aerospace application, to sustain high thermal barrier coatings, such as rocket nozzle (TiAl-SiC fibers),
- Engine parts (Be-Al), Heat Exchanger panels, wind tunnel blades, Spacecraft truss structure etc. With the continuous development in the field of FGM research, it is evident that the composition, structural properties (can be adjusted by gradient changes) can be tailored effectively, suiting a particular application [39].
- The use of FGM later expanded further into fields of industrial applications, automobile sector such as combustion chamber (SiC-SiC), Liners for engine cylinders (Al-SiC),
- CNG storage cylinder, diesel engine pistons(SiC_w / Al Alloy), Leaf springs, brake rotors, drive shafts (Al-C), Rocket nozzles, Wings, Rotary Launchers (Al alloy with Al_2O_3).
- Defense applications (Special type of armour development), Applications for Naval use focusing on submarine equipments (propulsion shafts (carbon & glass fibers)), cylindrical pressure hulls, (Graphite epoxy), sonar domes (glass / epoxy) composite piping systems etc and many more.

NEW AND INNOVATIVE DESIGN CONCEPTS OF FGCMS WITH NEW RESEARCH AND DEVELOPMENT INITIATIVES

Design of FGCMs

T. Fukushima et al (1990), Studied about FGM design including material design, material preparation and evaluation of material properties. FGM design is a sort of reverse design process i.e., first the ultimate structure of the material is conceived, along with its ambient application conditions, then from the FGM design data base suitable material, various transitional components of the properties and microstructure, as well as the preparation and evaluation methods and then, the design is framed up. According to Fukui. Y. et al [36], FGM design consists of three primary components:

- To determine structure and shape, Thermo-Mechanical boundary conditions and the composition distribution function.
- Identify data and composition material for thermal parameter model.
- The use of suitable mathematics-mechanical calculation methods, including FEL for calculation of stress distribution of FGM, using common self developed CAD software. Use of CAD system for design of FGM is primarily aimed at optimizing the design.

Fabrication of FGCMs

When FGM preparation is undertaken the primary focus, is on the appropriate means to achieve the composition of the FGM. The microstructure should be distributed, as designed to achieve the designed performance of the said FGM.

There are a variety of methods such as:

- Powder densification methods such as Powder Metallurgy (PM) process.
- Self Propagating High-temperature Synthesis (SHS) process.
- Coating Methods: Plasma Spray, Laser cladding, Electro-deposition method, Vapor deposition (physical vapor deposition and chemical vapor deposition) methods etc.

EXPERIMENTATION ON FABRICATION OF AL-SIC, AL-AL_2O_3 FGCM USING PM ROUTE

- Many methods for producing powders have been developed and standardized, for commercial exploitation, such as through electrolytic deposition, chemical reactions, grinding or comminution. Mass production rates of powders from different materials are possible, through the above methods. In PM process, the main criteria are focused on the precise weighing of the powders and the dispersion of the same in the mixture. These parameters will significantly affect the structural properties and hence be handled carefully.
- Subsequently, die compacting operation is performed at room temperature and followed by sintering is done at atmospheric pressure as elevated-temperature if used, may cause other reactions, which may affect the materials. At this stage, the ambient condition must be appropriate since high-temperature process has high sensitivity to the surroundings.

Discussed case study revealed the effect of systematic reinforcement of SiC or Al_2O_3, in layers to change the physico-metallurgical properties of the FGCM and this can be tailored, for intended use as described in above table. The hardness of Aluminium-Sic composites increased with increasing weight percentage of SiC due to dispersion hardening effect. Changes in the hardness of fabricated Aluminium-SiC FGCM have bright scopes for future aerospace application programs. Figure 3, is the FGCM made out of Al-SiC powder (a) Al side and (b) SiC side, before sintering; (c) and (d) in the same order after sintering; (e) and (f), in the same order the microstructure.

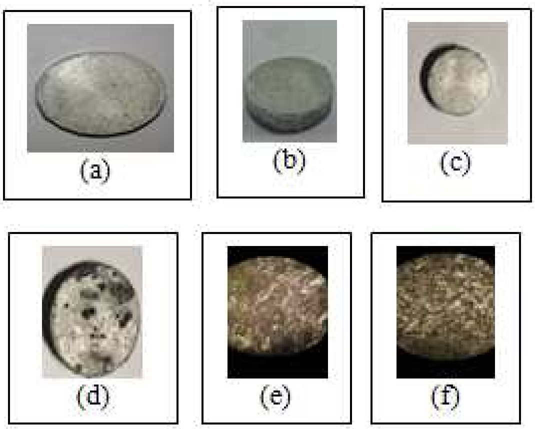

Figure 3: FGCM made out of Al-SiC Powder

Figure 4, shows the cylindrical cavity mould used, for pressing the FGCM. Figure 5, shows the automatic pressing machine for compacting operation and figure 6 shows SiC, Al and Al_2O_3 and binder used PVA (polyvinyl alcohol), in the experimentation of fabrication of the FGCMs.

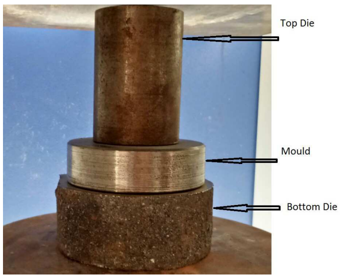

Figure 4: Cylindrical cavity mould

Figure 5: Automatic pressing machine for compacting

Figure 6: SiC, Al and Al_2O_3 Powders

Discrete layered FGM structure using Al-SiC is shown in Figure 7 and FG plate geometry, and coordinate system is shown in Figure 8.

Aluminium(100%)
Al(80%)-SiC(20%)
Al(60%)-SiC(40%)
Al(40%)-SiC(60%)
Al(20%)-SiC(80%)
SiC(100%)

Figure 7: Discrete layered FGM structure

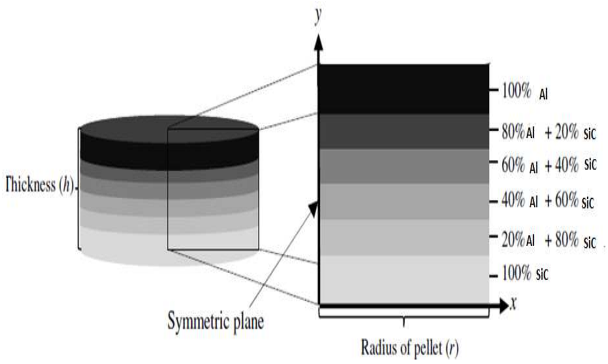

Figure 8: FG plate geometry and coordinate system

RESULTS AND DISCUSSIONS

The metallurgical microscope images at Fig 3 (e) & (f), show the Aluminium and 60% Silicon Carbide with 40% Aluminium side, a few more tests, on the morphology and particle distribution are underway, which will be described in our next paper. At different sintering temperatures the corresponding density, for the specimen is given below for reference.

Table2: Describe different Sintering Temperatures and Corresponding Sintered Density for FGCM Samples from Al-SiC Materials

Sintering Temperature, ℃	Sintered Density, %Th.
560	93.3
580	93.1
600	93.9
620	96.6

CONCLUSIONS

The development of FGMs has opened up, the path to new engineered materials for exclusive applications in areas such as aerospace, automobile, Nuclear Power plant, defense applications etc. This review is about establishing powder metallurgy (PM), as a better technique for large scale production and up scaling of FGCM. This was further strengthened, after considering the benefits of the technique, such as process cost efficiency, authenticity of the functional application of the process and high adequacy of the process, to control the quality of the FGM. It's been a great topic for research and development, as well as new application and has found prominence in all discussions, related to material science in recent times. Hence, it mandates new and novel approaches from all quarters, support and encouragement from research foundations, R & D Laboratories, corporate and engineering fraternity alike.

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